SULPHUR CONTENT OF SOILS AND ITS RELATION TO PLANT NUTRITION

CONTRIBUTIONS FROM THE HULL BOTANICAL LABORATORY **297**

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(ITH ONE FIGURE)

Introduction

Ever since the ten essential elements for plant nutrition were established by the work of SACHS, BOUSSINGAULT, NOBBE, and other investigators, sulphur has been recognized as one of them. The ash analysis method of determining sulphur in plants, however, which was in use during this early period, showed such a small amount present that the needs of the plant were thought to be amply taken care of by the supply in the soil. Contributions during the last twenty years by BERTHELOT, BARLOW, FRAPS, GOSS, BESTLE, SHERMAN, and others have shown that in ashing plant material much of the sulphur may be lost. The amount of sulphur in plants as determined by analyzing the ash may be only a fraction of the real amount. Thus the whole question of the relation of sulphur to plant nutrition has been reopened, for if plants use several times as much sulphur as had been supposed, then perhaps the supply in the soil is not sufficient for the needs of the plant. Recently there have been a number of contributions to the subject. The first questions to be considered have naturally been how much sulphur do crops use and what are the supplies to meet these needs. Thus the first problems to be investigated have been the sulphur content of crops, the sulphur content of soils, the amount of sulphur brought down by the rain, and the amount lost by drainage, etc. Next, sulphur was added to soils found to be low in it to see whether the yield of crops would be increased. In the present paper no attempt is made even to approximate a resumé of the sulphur literature, rather complete digests of which may be found in papers by CROCKER (4) and OLSON (19).

ROBINSON and co-workers (22, 23) have analyzed a number of soils from different parts of the United States. The sulphur content is not high, the average for thirty-five important agricultural soils being 0.052 per cent, with a range of 0.012–0.156 per cent. SHEDD (24) finds the soils of Kentucky much poorer in sulphur than in phosphorus, and is inclined to place sulphur in the same class with phosphorus, potassium, and nitrogen as one of the chief limiting factors in crop production. In pot experiments with some of these soils, tobacco, soy beans, turnips, radishes, mustard, and alfalfa were benefited by sulphur fertilization. AMES and BOLTZ (1) report analyses for certain Ohio soils. The unfertilized soils range in sulphur content from 0.020 to as high as 0.055 per cent. BROWN and KELLOGG (2) find nearly twice as much sulphur as phosphorus in some of the larger soil areas of Iowa. The Mississippi loess proves to be lowest, the soil samples in this area ranging in sulphur content from 441 to 847 pounds per two million pounds of soil. SWANSON and MILLER (27) have analyzed a number of the soils of Kansas and find that the cultivated soils analyzed have an average sulphur content of 0.027 per cent. Certain cultivated soils of Wisconsin, analyzed by HART and PETERSON (8), prove to be low in sulphur, the average being 0.020 per cent. They summarize the results of their analyses of a number of crops by stating that cereal crops remove from the soil about two-thirds as much sulphur trioxide as phosphorus pentoxide, the grasses of mixed hay as much sulphur as phosphorus, while the legume hays may take from the soil about as much sulphur as phosphorus, or, as in the case of alfalfa, more sulphur than phosphorus. Such crops as the cabbage and the turnip may remove two to three times as much sulphur trioxide as phosphorus pentoxide. REIMER and TARTAR (21) give analyses for a number of Oregon soils. The range in the sulphur content of the surface soils is 0.015–0.038 per cent. The phosphorus content is much greater. The sulphur fertilization of alfalfa grown on these soils produces greatly increased yields. Increased tonnage yields of 50–1000 per cent are secured, and the protein content is increased in some cases almost 2 per cent. In experiments in Washington by

OLSON (19), sulphur fertilization of alfalfa caused increased yields of 200–300 per cent.

The purpose of the present investigation was (1) to increase our knowledge of the sulphur content of soils, and (2) to study the relation of sulphur to chlorophyll development in certain plants and its effect on the yield of these plants. The phosphorus content of all the soils was also determined. Phosphorus, together with nitrogen, is considered the most generally limiting element of crop production in the soils of the United States. It was thought that it would be interesting to compare the sulphur content of the soils with their content of such an element as phosphorus.

Investigation

Soil analysis

It is important for American agriculture to discover how many soils in the United States are suffering from lack of sulphur, as are the Oregon soils to which reference has already been made. The Oregon results might be duplicated, perhaps, in the case of many other soils; on the other hand, many soils are probably not lacking in sulphur. The samples were chosen with a view of giving some idea of what range in sulphur content might be expected in the soils of the eastern and central United States. Thus, samples from the Atlantic and Gulf coast regions, from one of the southern states, from certain of the north central states, and from Chicago were analyzed. Investigations on the Atlantic coast during the early history of the United States showed great benefits from the use of gypsum as a fertilizer. It was thought that the analysis of certain of the coast soils might give some interesting results. On the other hand, soil analyses and sulphur fertilization tests in the central states may be said to indicate, in general, a higher sulphur content in the soils of this section than in the coast soils. It was desired to analyze a number of soils of the central states to compare with the coast soils. It is well known that rain carries down much more sulphur from a smoky atmosphere than from one less contaminated with smoke. It was thought that the Chicago soils might prove to have a very high sulphur content, owing to this fact.

Methods

Three methods of total sulphur determination were tested, the sodium peroxide method as evolved by HART and PETERSON (**8**), the VAN BEMMELEN method as modified by the same investigators, and a sodium carbonate fusion method, which was really a combination of KOCH's (**12**) sodium carbonate method for the determination of total sulphur in organic material and HILLEBRAND's (**10**) sodium carbonate method for the determination of total sulphur in rocks. The sodium peroxide method gave as high results as the other methods and better duplicates, and also was easier to manipulate. It was therefore adopted, but modified somewhat, and so it is given in some detail.

Ten grams of soil was placed in a 100 cc. nickel crucible, made quite moist with water, and 10 gm. of sodium peroxide added, a little at a time, stirring thoroughly with a nickel rod as the sodium peroxide was being added. This was heated slowly with a microburner until dry, and 10 gm. more of sodium peroxide added, spreading it over the surface, and continuing the heating until the surface layer melted. With a blast burner the mass was then brought to red heat and kept in this condition for ten minutes, stirring thoroughly. This was allowed to stand over a moderate flame for one hour, cooled, and the fused mass removed with boiling water, transferring it to a 600 cc. beaker. This was neutralized with concentrated HCl and then 10 cc. excess added, and allowed to stand on the steam bath for five or six hours, or until there was no undecomposed material in the bottom. It was next transferred to a 500 cc. volumetric flask, cooled, filled to the mark, and allowed to stand for four or five hours, shaking at intervals. A 250 cc. aliquot was filtered off, transferred to a beaker, a quantity of filter paper pulp added, and while stirring the iron, aluminum, etc., was precipitated out with ammonium hydroxide. This was heated for an hour on the steam bath, filtered into an 800 cc. beaker, and the precipitate washed with hot water until 600 cc. was obtained. After this it was heated to boiling, 10 cc. of hot 10 per cent barium chloride added to the boiling solution, and allowed to stand on the steam bath over night and at room temperature for the remainder of the twenty-four hours. The volume must not be allowed to decrease while on the steam bath. The solution was then filtered off from the barium sulphate, washed until no test for chlorides was obtained, the precipitate dried in an oven, and ignited to constant weight in a muffle furnace.

Part of the sulphur determinations reported later in this paper were obtained by igniting over a microburner, taking care that the paper was consumed without flaming up, but it was found that more uniformly successful results were obtained by igniting in a muffle furnace.

The iron and aluminum were removed because it was found that, in the case of a number of the soils analyzed, the barium sulphate precipitate was quite seriously contaminated by the iron. In the case of some of the soils analyzed during the preliminary work, the iron collected in masses on the bottom of the beaker. In other cases there was no contamination, or so little that the error introduced was small. It was decided, however, to make it a general practice to remove the iron and aluminum before adding the barium chloride solution. The chief difficulty encountered in the process was in washing out the sulphate ion from the iron and aluminum hydroxides. By using hot water, however, and having the precipitate well separated with paper pulp, the sulphate ion was completely washed out. It was found that there was some sulphur in the reagents used. Blanks were run and correction made for this.

The phosphorus was determined by the magnesium nitrate method as given in the Methods of Analysis of the Association of Official Agricultural Chemists (17). No important modification was made in the method. The ignition value given is the loss in weight obtained by heating the soil in the muffle furnace at red heat for an hour and a half. Two or three grams were used, and it was found that after heating for this length of time there was no loss of weight on further heating.

Data

In the following results of the analyses, the samples that proved to have the lowest sulphur content will be given first. The chief lack in the data is information as to the previous history of the soils from which the samples were taken. In a number of instances I have data as to the productivity of the soils, and information as to the amount of manure and fertilizer that had been applied to the soils in recent years, but in some cases it was impossible to secure this information. Also, the data would have more general significance, perhaps, if in all cases the names of the soil types could

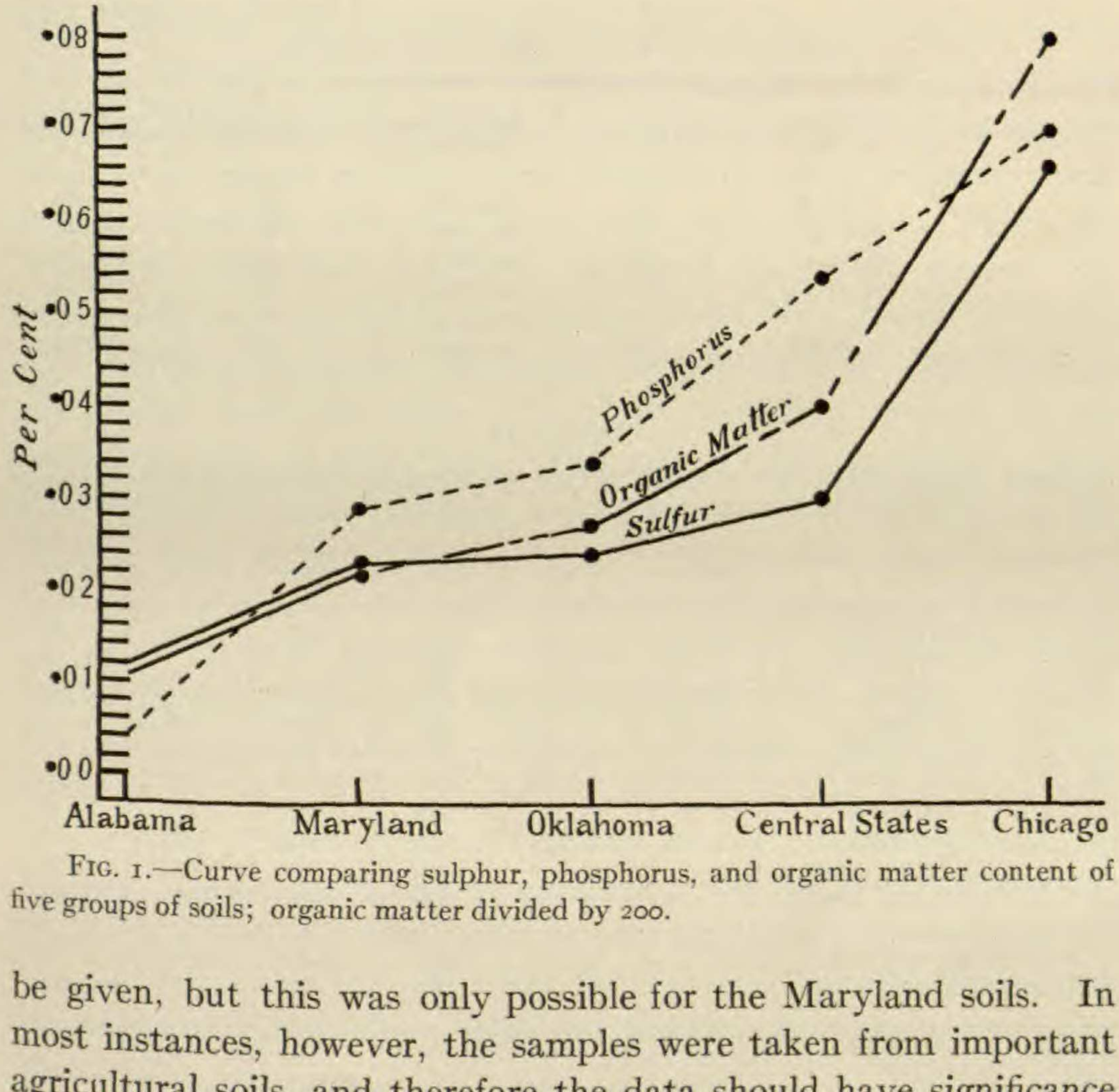

FIG. 1.—Curve comparing sulphur, phosphorus, and organic matter content of five groups of soils; organic matter divided by 200.

be given, but this was only possible for the Maryland soils. In most instances, however, the samples were taken from important agricultural soils, and therefore the data should have significance in adding to the information as to the sulphur content of the agricultural soils of different sections of the United States. All the results are figured on the basis of the oven-dry weight. The data concerning the pounds of sulphur per acre were obtained from the percentage of sulphur determined by analysis, by assuming that an acre of soil 6.5–7 inches in depth weighs 2,000,000 pounds.

Tables I and II give the results of the analysis of some soil samples from the Gulf coast and the Atlantic coast. I am indebted to Dr. A. G. McCall, of the University of Maryland, for the Maryland samples, and also for the information in regard to the productivity of the soils. Little information was obtainable in regard to the samples of table I, except that they came from soils

TABLE I

SULPHUR, PHOSPHORUS, AND ORGANIC MATTER CONTENT OF CERTAIN ALABAMA SOILS (NEAR MOBILE BAY), TAKEN FROM SURFACE

Sample no.	Percentage sulphur	Lb. per acre	Percentage phosphorus	Lb. per acre	Ignition value
15..........	0.0090	180	0.0028	56	2.189
16..........	0.0148	296	0.0044	88	2.127
17..........	0.0151	302	0.0067	134	2.256
18..........	0.0126	252	0.0044	88	2.204
Average...	0.0128	256	0.0045	90	2.194

TABLE II

SULPHUR, PHOSPHORUS, AND ORGANIC MATTER CONTENT OF CERTAIN MARYLAND SOILS

Sample no.	Location (county)	Depth inches	Percentage sulphur	Lb. per acre	Percentage phosphorus	Lb. per acre	Ignition value
23.......	Worcester	0–7	0.028	560	0.015	300	2.48
24.......	Worcester	7–28	0.023	460	....	....	1.58
25.......	Talbot	0–7	0.023	460	0.026	520	4.39
26.......	Talbot	7–28	0.015	300	0.012	240	4.71
27.......	St. Mary's	0–7	0.018	360	0.026	520	4.66
28.......	St. Mary's	7–28	0.020	400	0.018	360	4.54
29.......	Howard	0–7	0.019	380	0.048	960	6.33
30.......	Howard	7–28	0.014	280	0.044	880	6.14
31.......	Prince George	0–7	0.030	600	0.030	600	4.81
32.......	Prince George	7–28	0.019	380	0.026	520	4.91
Average surface soils............			0.023	460	0.029	580	4.53
Average subsoils................			0.018	360	0.025	500	4.37

on which the attempt was being made to grow pecans. The soils are so low in sulphur, phosphorus, and organic matter that it would seem impossible to grow any crop successfully on them without considerable fertilizing.

Samples 23 and 24 of table II belong to the soil type known as Norfolk fine sandy loam. The field from which the samples were taken is fairly productive, being capable of producing ten bushels of wheat or thirty bushels of corn per acre. The samples from Talbot County belong to the Elkton silt loam type of soil. It is not very productive, and has to be fertilized rather heavily to produce very good crops. The soil represented by samples 27 and 28 is known as the Leonardtown silt loam type of soil. It has rather low productivity, producing about 500 pounds of tobacco or seven bushels of wheat per acre. The samples from Howard County belong to the Chester loam soil type, which is one of the best soils in the state, producing sixty-five bushels of corn or twenty bushels of wheat per acre. Samples 31 and 32 belong to the sassafras silt loam type. This is a fairly good soil, producing ten bushels of wheat or thirty-five bushels of corn per acre. The samples from St. Mary's County and from Howard County are from soils that had not been fertilized in recent years. The other soils have probably received recently little if any fertilizers. The Maryland samples are rather few in number, but are well distributed over the state. They are probably typical for the cultivated soils of Maryland. The soils are low in sulphur, phosphorus, and organic matter; somewhat lower in sulphur on the average than in phosphorus. It would seem that they should be benefited by the use of both sulphur and phosphorus as fertilizers.

Table III is an attempt to make a further study of the Maryland soils, using as a basis the productivity data and the data for the surface soils of table II. The second column shows the relative order of the five soils in productivity, beginning with the most productive. There does not seem to be any relation between the sulphur content and the productivity. When we consider the phosphorus content, however, the two best soils as to productivity are also highest in phosphorus. This relation between phosphorus content and productivity does not hold in the case of the other three soils, but here the phosphorus content is so low that other factors may be limiting production. It would seem possible, therefore, especially in the case of the fields from which the Chester loam and sassafras silt loam samples came, that phosphorus rather than sulphur was limiting production. The Chester loam soil especially should be considered. It is one of the best soils of the state and in its phosphorus content also it is decidedly higher than any other of the soils analyzed. The order of the soils as to the organic matter content is about the same as their order considered on the basis of the phosphorus content. It might be that the relatively large amount of organic matter in the Chester loam and the sassafras silt loam soils is a factor in their productivity. Organic matter improves the tilth of soils, adds plant food, and has other important effects.

Their relative ability to produce cereal crops is used as a measure of the productivity of the soils. Cereal crops require more phosphorus than sulphur. It might well be that, if the production of a high sulphur containing crop (alfalfa, for instance) was taken as the criterion, the order of the soils in table III would be different. Even if phosphorus, rather than sulphur, is at present the limiting

TABLE III

RELATIVE ORDER OF THE FIVE MARYLAND SOILS IN PRODUCTIVITY, SULPHUR, PHOSPHORUS, AND IGNITION VALUE

Soil type	Productivity	Sulphur	Phosphorus	Ignition value
Chester loam	1	4	1	1
Sassafras silt loam	2	1	2	2
Norfolk fine sandy loam	3	2	5	5
Leonardtown silt loam	4	5	3	3
Elkton silt loam	5	3	3	4

factor in these soils, sulphur would no doubt soon become the limiting factor if the level of supply of the phosphorus is raised by adding phosphorus fertilizers. The sulphur supply is so low that, with phosphorus removed as the limiting factor, it might become the limiting factor to production.

Of course it is realized that too great reliance should not be placed in a soil analysis, especially such a soil analysis as this, where only two of the several elements needed by plants are determined. At the most, a soil analysis only shows the total amount of plant food present and does not tell anything as to the availability of the elements. Also, other factors than plant food may be limiting production, but a soil analysis should develop some leads, which can be followed up by other methods of attack.

Since the data show a rather low sulphur content in the few Atlantic coast and Gulf coast soils analyzed, it might be of interest to see what results have been obtained from using sulphur as a fertilizer in these regions. Very little work of this kind has been done. Several stations report a favorable effect from using phosphorus or potassium as a fertilizer for alfalfa, when the carrier of the phosphorus or potassium also contained sulphur. The Delaware station (7), for example, reports greatly increased yields of alfalfa due to acid phosphate. Experiments in Oregon (21) have shown a decided increase from applying acid phosphate to soils, but no increase due to phosphorus in any other form. Here it has been definitely proved that the increased yield caused by acid phosphate was due to the sulphur of the acid phosphate, and not to the phosphorus. It would seem worth while to test this in the case of the Delaware soils. The Virginia station (3) secures increased yields of alfalfa due to phosphorus in the form of acid phosphate and basic slag, but not in the case of other forms of phosphorus, such as rock phosphate. Here again we have the possibility that sulphur is responsible for the increased yields. The Massachusetts station (16) finds sulphate of potash a better fertilizer for alfalfa than muriate of potash. The alfalfa of the sulphate of potash plats was also a darker green. Clearly these results are due to the sulphur present in the sulphate of potash, and not to any differences in the potassium.

The best experiments on the Atlantic coast to show the effect of sulphur fertilization on crops are those of the investigators of the colonial period, whose work is summarized by CROCKER (4). PETERS and BINNS were the most prominent of these investigators. They performed numerous experiments showing the effect of gypsum on crop yield. Leguminous crops especially were benefited, red clover giving increased yields of two to threefold. BINNS reported like increased yields for corn and wheat. Although the reports of the experiments do not make this clear, it seems likely that the beneficial effects of gypsum on the non-leguminous crops was due to the increased nitrogen supply brought about by the greater growth of the legumes of the rotation. RUFFIN was also greatly impressed by the results obtained from the use of gypsum as a fertilizer. In his *Essay on calcareous manures* he speaks of the magic effects obtained from applying gypsum as a fertilizer to clover. Considering the results of the writer's analyses, together with the other experimental work to which reference has been made, it would seem worth while to test sulphur as a fertilizer throughout the Atlantic coast region.

The samples of table IV were taken in cultivated fields near Miami, Oklahoma, two of the samples from one field and two from another. Nothing is known as to the previous treatment of the soils from which the samples came, or it might be possible to answer some questions which arise from a study of the data, such as the reason for the much greater phosphorus content of samples 21 and 22 than of samples 19 and 20.

TABLE IV

SULPHUR, PHOSPHORUS, AND ORGANIC MATTER CONTENT OF CERTAIN SOILS NEAR MIAMI, OKLAHOMA

Sample	Depth	Percentage sulphur	Lb. per acre	Percentage phosphorus	Lb. per acre	Ignition value
19........	Surface	0.0202	404	0.0107	214	4.346
20*.......	Subsoil	0.0287	574	0.0087	174	7.764
21........	Surface	0.0278	556	0.0587	1174	6.710
22*.......	Subsoil	0.0136	272	0.0543	1086	5.290
Average surface soil...		0.0240	480	0.0347	694	5.528
Average subsoils......		0.0211	422	0.0315	630	6.527

* It is not certain that subsoils 20 and 22 go with soils 19 and 21 respectively; they were arranged with these soils on the basis of color.

Table V contains the results of the analyses of certain soils of the central states. Samples 3 and 4 were taken in an alfalfa field; samples 5 and 6 in an oat field. The alfalfa field had been manured with one and one-half tons of cow manure per acre in 1918. The oat field had received in the same year an application of two tons per acre of cow manure. Both fields had been fertilized with gypsum in 1920. Samples 7, 8, 9, and 10 were all taken in one field of seven acres, which had been in grass for many years. This field was put in corn in 1920, producing only a fair crop. In the fall of 1920 it was put in alfalfa. Sample 33 is a composite sample taken in a clover field near Paris, Illinois. Trouble was being experienced in growing clover on part of the field. It was thought that this might be due to the low sulphur content of this part of the field, but soil analysis indicated that such was not the case. In fact, one of the samples from soil supporting a good stand of clover contained decidedly less sulphur than did any of the samples from the part of the field where there was no clover. It would seem that some other factor than the sulphur content was preventing the growth of clover. Since the results of analysis revealed no reason for the failure to secure a good stand of clover on part of the field, the data for all the samples were averaged in order to secure an average value for the entire field.

TABLE V

SULPHUR, PHOSPHORUS, AND ORGANIC MATTER CONTENT OF CERTAIN SOILS OF CENTRAL STATES

Sample no.	Location	Depth	Percentage sulphur	Lb. per acre	Percentage phosphorus	Lb. per acre	Ignition value
1....	Fremont, Ohio	0–7	0.029	580	0.056	1120	6.87
2....	Fremont, Ohio	7–20	0.015	300	0.048	960	6.72
3....	Plattesville, Wis.	0–7	0.028	560	0.034	680	4.47
4....	Plattesville, Wis.	7–20	0.038	760	0.040	800	5.62
5....	Plattesville, Wis.	0–7	0.034	680	0.040	800	5.26
6....	Plattesville, Wis.	7–20	0.019	380	0.036	720	6.74
7....	Naperville, Ill.	0–7	0.021	420	0.060	1200	10.17
8....	Naperville, Ill.	7–20	0.030	600	0.040	820	8.40
9....	Naperville, Ill.	0–7	0.040	800	0.051	1002	9.32
10....	Naperville, Ill.	7–20	0.020	400	0.052	1004	9.71
11....	Gilman, Ill.	0–7	0.058	1160	0.086	1720	13.53
12....	Gilman, Ill.	7–20	0.035	700	0.120	2400	10.76
13....	Gilman, Ill.	0–7	0.029	580	0.045	900	6.71
14....	Gilman, Ill.	7–20	0.036	720	0.057	1140	8.43
33....	Paris, Ill.	0–7	0.030	600	0.056	1120	7.40
Average surface soils............			0.030	600	0.054	1080	8.00
Average subsoils................			0.027	540	0.056	1120	8.05

Particular attention is called to the samples from Gilman, Illinois. These were received from Mr. F. I. MANN, who also supplied the information in regard to the previous treatment of the land from which the samples came. They were all taken in the same field. Samples 11 and 12 came from a part of the field that during sixteen years had received applications of rock phosphate and ground limestone. No other fertilizer had been applied to the land for at least twenty years, and not much before that. Samples 13 and 14 came from the check part of the field, which had received no fertilizer of any kind. Clover had been grown on the field once in four years, about half of the crop being plowed under. Clover was also grown on the check part of the field. Very little grew here, however, and so there was not much to plow under. Mr. MANN stated that the amount of phosphorus applied to the land where samples 11 and 12 were taken would just about equal that naturally present in the soil, so that these samples would be expected to contain about twice the phosphorus of the samples from the check portion. Table V shows this to be the case, but the sulphur content of the surface soil of the fertilized land is also double that of the check portion. This is rather to be expected, when we compare the two in their organic matter content. Sample 11 is about double that of sample 13, and a high organic matter content usually means a high sulphur content. The question, however, is as to the source of supply of the sulphur. No sulphur fertilizers have been applied to the land. There is the possibility that, since the clover plant makes considerable growth during the time of the heavy rains of the spring and again in the fall after the rains start (times when the sulphur content of rainwater is rather high), some of the sulphur might come from this source. It is not believed, however, that the sulphur brought to the land by the rain results in a net increase in the sulphur content of the soil, on account of the large amount of sulphur lost in drainage, although the amount lost in drainage is greatly decreased when the land is covered by a crop. There is the additional possibility that the clover roots bring up sulphur from the subsoil, depositing it in the surface layers. As shown by the data, the subsoil of the fertilized part of the field has about the same sulphur content as the soil and subsoil of the check portion. Some of the other soil analyses have shown that the sulphur content of various parts of the same field may vary widely, when all parts of the field have been treated alike so far as sulphur fertilization is concerned. If this is true in the present case, then the difference in the sulphur content of the two parts of the field would not be significant, but the high organic matter content of the fertilized part of the field would seem to indicate that these samples are representative, and that there really is here a high sulphur content.

Considering all the samples of table V, it may be said in summary that the sulphur content on the average is not high in amount, although somewhat greater than the Maryland and Oklahoma soils, and decidedly greater than the Alabama soils. The phosphorus content is also rather low, although much higher than the sulphur content. There is a fair amount of organic matter present on the average in the soils. Reference was made previously to certain soil analyses in Kentucky, Iowa, Kansas, Wisconsin, and Ohio. Judging from my analyses and those referred to in the introduction, many soils in the middle states need sulphur. Some of them are well supplied, however, and on the average they seem to have a higher sulphur content than the soils of either the Atlantic or Pacific coasts, although not enough analyses or fertility experiments have been made to make a positive statement as to this. On the other hand, some of the soils are as low in their sulphur content as any of the coast soils, so that it would not be surprising if sulphur should prove beneficial on these soils. Demonstration experiments on as many of the central states soils as possible are needed to determine how generally sulphur is deficient.

Not many experiments of this kind have been performed. Certain investigators in Kentucky (25), Wisconsin (9, 28), and other states, in pot experiments, have secured increased yields from sulphur fertilization in the case of alfalfa, clover, radishes, rape, turnips, mustard, tobacco, and soy beans. In field experiments, JARDINE and CALL (11) attribute the increased yields in Kansas secured by fertilizing alfalfa with acid phosphate to the phosphorus of the acid phosphate, but here again there is the possibility that the sulphur contained in the acid phosphate is at least partly responsible for the increased yields. During the last few years the Gypsum Industries Association has conducted a number of experiments, seeking to determine the value of gypsum as a fertilizer for crops. Beneficial effects have already been secured in a number of cases. Such work should be extended.

Table VI records the results of the analysis of a few samples taken within the environs of Chicago. Each sample includes a number of borings and is therefore composite. The sample from the South Chicago region was taken from what seemed to be a natural prairie. This soil had probably never been fertilized. The Midway, where samples 39 and 40 were taken, is quite often manured. It was learned after analyses were made that samples 41 and 42 were taken from a part of the botany gardens that had been filled in. The subsoil especially of this sample is not typical, its higher sulphur content than the subsoils of the other soils probably being accounted for by the filling in. The few Chicago soils analyzed are all much better supplied with sulphur, phosphorus, and organic matter than any of the other soils analyzed. It may be that soils of as high a sulphur content as these Chicago soils might not need any sulphur fertilization, although in the case of certain high sulphur-using crops the available sulphur might not be sufficient. All the samples were taken from soils overlaid with sod, and have a high organic matter content. There are probably many soils in Chicago of much lower sulphur and organic matter content, which might need sulphur fertilizers.

TABLE VI

SULPHUR, PHOSPHORUS, AND ORGANIC MATTER CONTENT OF CERTAIN CHICAGO SOILS

Sample no.	Location	Depth	Percentage sulphur	Lb. per acre	Percentage phosphorus	Lb. per acre	Ignition value
39....	Midway	0–8	0.060	1200	0.100	2000	15.25
40....	Midway	8–26	0.021	420	0.055	1110	10.24
41....	Botany Gardens	0–8	0.055	1110	0.073	1460	15.79
42....	Botany Gardens	8–26	0.045	900	0.068	1360	13.08
43....	South Chicago	0–8	0.069	1380	0.038	760	17.11
44....	South Chicago	8–26	0.023	460	....	....	15.12
Average surface soils............			0.061	1220	0.070	1400	16.05
Average subsoils................			0.029	580	0.060	1200	12.81

It was thought interesting to determine how much of the total sulphur of the Chicago soils might be accounted for by the sulphate sulphur content. As is well known, where much soft coal is burned, much sulphur is given off. It would be expected, therefore, that rain would carry to the soil much more sulphur from a smoky atmosphere than from one free from smoke. WARRINGTON (quoted by HART and PETERSON (8)) gives the amount of sulphur carried to an acre surface of soil at Rothamsted as about seven pounds per year. Judging from their limited data, HART and PETERSON (8) estimate about the same figures are correct for University Hill Farm, Madison, Wisconsin. Data indicate a much higher sulphur content of the rainwater of cities. Some of my determinations show several times as much sulphur in Chicago rainwater as in rainwater collected in the country some distance from Chicago. Most of the sulphur in rainwater is in the sulphate form. It might be expected, therefore, that the sulphate sulphur present in the Chicago soils might account for much of the total sulphur. Roughly quantitative determinations showed an average sulphate sulphur content of the three surface soils of table VI of 158 pounds per two million pounds of soil. This is high, compared with the Iowa soils as analyzed by BROWN and KELLOGG (2). They found an average sulphate sulphur content of 59 pounds per two million pounds of soil, but the sulphate sulphur present in the Chicago soils accounts for comparatively little of the total sulphur. Most of this is in the organic form, and the high sulphur content of the soils is due mainly to the high organic matter content. That the sulphate sulphur content is not higher may be accounted for probably by the ease with which sulphur in a soluble form is leached from the soil.

LYON and BIZZELL (14), MACINTIRE and co-workers (15), and other investigators have performed lysimeter experiments. LYON and BIZZELL show that 3–6 times as much sulphur is lost in drainage as is used by the crop, and when put in a soluble sulphate added to the tanks, over one-half of the amount added in any one year was removed in drainage the same year.

Table VII summarizes the data of tables I, II, IV, V, and VI. Fig. 1 compares in a graphical way the sulphur, phosphorus, and organic matter content of the five groups of soil. The Alabama, Maryland, and Oklahoma soils are all low in sulphur, phosphorus, and organic matter, the Alabama soils being especially deficient in all three substances. The phosphorus, on the average, is not much greater in amount than the sulphur. Although the central states soils are better supplied with sulphur and phosphorus than these three groups of soils, they would not be considered high in either. The range in the amount of sulphur and phosphorus present in the various soils is rather great. Certain of the soils would be considered fairly well supplied with both sulphur and phosphorus. The organic matter content of the soils is on the average fairly good, although here also the range is very great, and certain of the soils are deficient in this respect.

The sulphur and phosphorus content of the Chicago soils is fairly good, while the organic matter content is high. As is brought out in connection with table VI, the samples are not typical for the cultivated soils of Chicago and its environs. They were taken in places where the organic matter had had a chance to accumulate. Their high sulphur content is to be accounted for mainly by their high organic matter content, the sulphur brought down by the rain accounting for little of the total sulphur. Although the Chicago samples should not be considered typical for cultivated soils, they are perhaps typical of soils of any section of the United States which have been in grass or any form of plant

TABLE VII

SUMMARY OF TABLES I, II, IV, V, AND VI, GIVING AVERAGE OF SURFACE SOILS; SULPHUR AND PHOSPHORUS IN POUNDS PER ACRE, IGNITION VALUE IN PERCENTAGE

	Alabama	Maryland	Oklahoma	Central states	Chicago
Sulphur	256	460	480	600	1220
Phosphorus	90	580	694	1080	1400
Ignition value	2.194	4.53	5.528	8.00	16.05
Ratio ignition value to sulphur	182.5	196.9	230.0	263.3	263.1

life for a number of years, or have been heavily manured. Such soils would be expected to be well supplied with organic matter, and to have a correspondingly high sulphur content. If conditions are right for active sulphofication, there should be an abundance of available sulphur.

A further study has been made of this relation between the organic matter and total sulphur of the different groups of soils by determining the ratio of the organic matter to the total sulphur. As shown by table VII, this ratio is far from a constant. A 100 per cent increase in the organic matter content does not mean a corresponding 100 per cent increase in the sulphur content. A comparison of the ratios for the different groups of soils, and of the figures for the sulphur content and the organic matter content seems to justify the statement, however, that there is a general correlation between the two, that a soil with a large amount of organic matter also contains a large amount of sulphur. That the correlation is not closer may be accounted for, at least in part, by the fact that plants differ greatly in their sulphur content. The source of the organic matter present in the soil has a great deal to do with the amount of sulphur the soil contains. This fact may account, at least partly, for the cases (shown by the tables giving the detailed data of the soil analyses) in which there does not seem to be any correlation at all between the organic matter and sulphur content. A high organic matter content may be correlated with a low sulphur content, but these cases should be considered exceptions to the general rule that a soil containing a large amount of organic matter also contains a large amount of sulphur, a rule which is seen more clearly when the sulphur and organic matter content of a number of soils are averaged. In general, the sulphur content of soils is greater than that of the corresponding subsoils.

Table VIII gives the number of crops that could be grown from the amount of sulphur present in the various groups of soils as summarized in table VII. BROWN and KELLOGG'S (2) figures for the amount of sulphur removed by maximum yields of these crops have been used. They assume that the entire crop is removed from the soil. In the Maryland and central states soils, which include the most important agricultural soils, the number of crops supply of sulphur in the poorest soil and in the best soil is given in the column "Range." Table VIII shows that there is enough sulphur present in most of the soils for comparatively few maximum crops of such high sulphur-containing plants as alfalfa and potatoes. The other crops contain less sulphur, and therefore a greater number of maximum crops of these could be grown.

Most of the sulphur of the different soils is in the organic form and unavailable for the plant, and it is not known how rapidly sulphofication is making it available. When the sulphur content of a soil is as low as it is in the Alabama, Maryland, Oklahoma, and several of the central states soils, however, sulphofication may not produce enough available sulphur to secure maximum yields of most crops. Considered from this standpoint, table VIII may not be very significant, except as another way of comparing the sulphur content of the different groups of soils.

The sulphur content of maximum yields of the six crops given in table VIII, according to the figure of BROWN and KELLOGG, totals 134.3 pounds; the total phosphorus content 128 pounds. These are five of the most common crops, especially in the central states. Judging from the soil analyses that have been made by

TABLE VIII

NUMBER OF MAXIMUM CROPS THAT MAY BE GROWN FROM AMOUNT OF SULPHUR PRESENT IN THE FIVE SOIL GROUPS AS GIVEN IN TABLE VII

	Alabama	Maryland	Range	Oklahoma	Central states	Range	Chicago
Corn	16	28	22–37	30	37	26–72	76
Wheat	25	45	35–58	47	58	41–113	119
Oats	15	27	21–36	29	36	25–70	73
Potatoes	7	14	11–17	14	18	12–35	37
Clover	19	35	27–45	36	45	32–88	93
Alfalfa	5	10	7–13	10	13	9–25	26

various investigators, the agricultural soils of the United States are even more deficient in sulphur than in phosphorus. Although considerable sulphur is added to the soil of rainwater, a larger amount seems to be lost in drainage, some investigators stating that three times as much sulphur is lost from the soil in drainage as is added to the soil by the rain. It would seem possible, therefore, that further investigation would prove that sulphur is as generally needed as a fertilizer as is phosphorus.

EFFECT OF SULPHUR ON CHLOROPHYLL DEVELOPMENT, AND GROWTH OF RED CLOVER AND SWEET CORN

Several investigators have reported a better color in plants due to sulphur fertilization. REIMER and TARTAR (**21**), as already stated, secured greatly increased yields of alfalfa from sulphur fertilizers. They emphasize the poor color of the alfalfa on the plats not fertilized with sulphur. OLSON (**19**) speaks of the same thing in connection with experiments in Washington. The Massachusetts station (**16**) reports like results, but the beneficial effect on the color does not seem to be confined to the legumes. DULEY (**6**) reports the same thing in the case of sweet corn, and DEMOLON

(5) observed a darker green in the foliage of rutabagas, parsnips, and beets fertilized with sulphur than in the check experiments. An experiment was planned to try to determine the relation between the sulphur and the chlorophyll content of the plants. STOWELL'S evergreen sweet corn and mammoth red clover were grown in ordinary 12-inch flower pots. Thirty-six pounds of sand were added to each pot. For series 1, 2, and 3 pure quartz sand was used; for series 4, 5, 6, 7, and 8 a fine grade of torpedo sand sifted free from stones and coarse material was used. Sulphur was added to the sand, as shown in table IX. The figures in the table mean that sodium sulphate and flowers of sulphur were added in such amounts as to give the same amount of sulphur as contained in

TABLE IX

AMOUNT OF SULPHUR ADDED TO SAND CULTURES OF CLOVER AND SWEET CORN

Series	Flowers of sulphur (lbs.)	Sodium sulphate (lbs.)	Gypsum (lbs.)
1			
2		100	
3	100		
4		300	
5	300		
6		500	
7	500		
8			500

100, 300, and 500 pounds of gypsum per acre, or two million pounds of sand. Each series was run in triplicate.

The gypsum and flowers of sulphur were thoroughly mixed with the sand at the time the pots were filled. The sodium sulphate was added in solution in three applications. The corn was harvested sooner than had been planned, and received only two applications of sodium sulphate. The sodium sulphate series in the case of the corn, therefore, received two-thirds of the amount given in the table. In addition lime was added at the rate of 1000 pounds per two million pounds of sand. One week after the cultures were started 1 gm. of ferric chloride was added to the sand of each pot. The corn was planted February 7. It had previously been placed between moist filter paper, and at the time of planting all the seeds were fully imbibed and most of them had sprouted. The clover was sown January 22, and on February 6, when the plants were 4 inches high, they were transplanted to the sand. A pure culture inoculum obtained from the Department of Bacteriology of the University of Wisconsin was added to the sand containing the clover on February 13.

The nutrient solution used was the same as that used by KRAUS and KRAYBILL (13), except that magnesium chloride was substituted for magnesium sulphate. Perhaps a solution better suited to corn and clover might have been found, but it gave good growth in both cases. It was made up as follows:

SOLUTION *A*	Per cent	SOLUTION *B*	Per cent
Magnesium chloride	2	Calcium nitrate	8
Dibasic potassium chloride	2		
Potassium nitrate	2		

Equal parts of *A* and *B* were diluted 1 to 70 with water and then mixed. The solution was applied in this strength to the corn. The solution applied to the clover was just half this strength. Five hundred cc. of these solutions were added on an average of once a week to the corn and the clover. While the plants were small and the light poor, not so much was applied, but later the supply was increased. Both the corn and clover grew well, but no marked differences in color or size of plants developed in either In fact, in the case of the corn, that in the control series was as green as the corn of any of the other series. It was not deemed the right kind of material for studying the effect of sulphur on chlorophyll development, and no chemical analyses were made.

Since no marked differences in color or growth due to sulphur deficiency had developed in the clover of the different series, it was decided to modify the experiment somewhat. It was thought the nitrate supply might be too high. On April 27 each series was divided into two parts. The nitrates were kept up in one-half of the pots and discontinued entirely in the other half, but no marked differences in color had developed at the time the experiment was stopped, on May 27. At this time the clover of the control series was somewhat paler than the clover of the high sulphur pots, but it was not very marked. Also, no definite gradation in color from the control series to the high sulphur series was discernible. The microchemical analyses were made on the clover of the control series and the clover of the high sulphur series, in the latter case using mainly plants from series 8, the gypsum series.

The most noticeable point in table X is that the nitrates, protein, and sulphates are greater in amount in the plants of the high gypsum series. There was not much difference in the carbohydrate situation in the two series. Leaves from plants of the two series had about the same amount of reducing sugars and starch. The petioles of the control plants contained more reducing

TABLE X

MICHROCHEMICAL ANALYSES OF CLOVER PLANTS OF CONTROL SERIES AND OF HIGH SULPHUR SERIES; NITRATES DISCONTINUED MAY 27

	$CaSO_4$ HIGH			$CaSO_4$ NONE		
	Leaves	Petioles	Roots	Leaves	Petioles	Roots
Nitrates......	+	++	++	+	+	+
Protein.......	+	++	++	+	+	+
Sulphates....	++	++	++	+	+	+
Sugar........	+	+	++	+	++	++
Starch.......	+	++	++	+	++	+

sugar than in the case of plants from the high gypsum series, but the starch content of the petioles was about the same in both. In the roots, the reducing sugar was about the same in amount in both series, while the starch was greater in amount in the gypsum series. These differences, while clearly evident, were not great enough to permit any definite conclusions as to the relation of sulphur to chlorophyll development in the clover plant.

REIMER and TARTAR (21), MILLER (18), DULEY (6), and HART and TOTTINGHAM (9) have shown that root development and nodule formation are increased in clover and alfalfa by the use of sulphur fertilizers. PITZ (20) has shown that sulphur causes an increase in the nodule-forming bacteria of 2–3 fold. REIMER and TARTAR have also demonstrated that sulphur increases the nitrogen content of alfalfa 2–3 per cent. SCHERTZ (26) has shown a close connection between the nitrogen and chlorophyll content of *Coleus* leaves, so that it is possible that sulphur has at least part of its effect through increasing the nitrogen content of the plant. My work seems to indicate this, but more work is desirable before coming to any definite conclusions. In the case of the non-legumes, the activity of ammonifying and nitrifying bacteria of the soil might be increased. The evidence is conflicting as to the effect of sulphur on these organisms, some claiming a favorable effect and some little effect. It is hoped to repeat this experiment, both in the case of corn and clover, omitting the nitrates entirely or keeping them very low. This should be done from the start; then, if the sulphur does have its effect indirectly by increasing the nitrogen supply through an increase in the number and activity of these organisms, this effect should be apparent. Special precautions should be taken to exclude sulphur. Sulphur-free salts, of course, should be used. The sand should be thoroughly washed with distilled water, perhaps even boiled in acid and then washed with distilled water, to eliminate any sulphur that it may contain. If decided differences in color develop, as a result of sulphur deficiency, the microchemical analyses should be followed by quantitative chemical analyses.

Table XI gives data concerning the effect of sulphur in different forms and different amounts on the growth of sweet corn. As before stated, the corn was grown with the idea of obtaining material to study the effect of sulphur on chlorophyll development in non-legumes. Since no difference in color in the different series developed, the corn was harvested and the dry weight determined, to see the effect of sulphur on the growth. It had been growing about two and one-half months and was in tassel. The details of the plan of the experiment have already been given. The numbers in the column "Treatment" indicate that flowers of sulphur and sodium sulphate were added in such amounts as to contain the same amount of sulphur as present in 100, 300, or 500 pounds of gypsum per acre, or two million pounds of sand. The percentage increase or decrease is based upon the dry weight. The minus sign indicates a decrease.

Series 4 should not be considered, for from the first the corn in two of the pots of this series did not grow well. At the time of harvest most of this corn was short and spindling. This is believed to be due not to the sulphur treatment but to poor seed. Leaving this series out of consideration, we see that flowers of sulphur and sodium sulphate containing the same amount of sulphur as 100 pounds of gypsum, and gypsum at the rate of 500 pounds per acre gave marked increased dry weights over that of the control. The flowers of sulphur caused the greatest increase, 66.16 per cent,

TABLE XI

EFFECT OF DIFFERENT SULPHUR TREATMENTS ON GROWTH OF STOWELL'S EVERGREEN SWEET CORN IN GREENHOUSE

Series	Treatment	Moisture	Green weight (gm.)	Dry weight (gm.)	Percentage increase or decrease
1........	Control	87.62	266.7	33.1	....
2........	Na_2SO_4 at rate of 100 lb. gypsum per acre	86.60	334.0	44.8	35.34
3........	Flowers of sulphur at same rate as 2	85.12	369.6	55.0	66.16
4........	Na_2SO_4 at rate of 300 lb. gypsum per acre	85.00	164.3	24.7	−25.37
5........	Flowers of sulphur at same rate as 4	84.95	217.8	32.8	− 0.90
6........	Na_2SO_4 at rate of 500 lb. gypsum per acre	85.44	222.5	32.4	− 2.11
7........	Flowers of sulphur at same rate as 6	85.93	237.2	33.4	0.90
8........	Gypsum at rate of 500 lb. per acre..............	82.76	271.7	46.9	41.69

and gypsum was next with 41.6 per cent, sodium sulphate causing 35.3 per cent increased dry weight. It is hard to say why flowers of sulphur and sodium sulphate in the larger amounts did not bring about increased growth. The dry weight of these series is about the same as the check.

There has been work indicating injury to plants by the acid resulting from the oxidation of flowers of sulphur. Also some have claimed injury from the alkalinity developed in the soil by sodium salts. While this is a possibility, it is not emphasized. The acidity should have been taken care of by the calcium carbonate added to the sand. The literature shows that sulphur fertilization of cereals has not given consistent results, and as a rule not a very marked increased growth has been caused, so perhaps no particular significance should be attached to the fact that series 5, 6, and 7 show about the same dry weights as the check. The corn of all the series where sulphur fertilizers were used had a lower moisture content than the corn of the control series, the corn fertilized with gypsum having about 5 per cent less moisture than the control.

Summary

1. The Alabama, Maryland, and Oklahoma soils analyzed are low in sulphur, phosphorus, and organic matter; the phosphorus being not much greater in amount than the sulphur. The central states soils are better supplied, on the average, in all three respects, and decidedly better supplied with phosphorus than with sulphur. Some of these soils might be considered to have a fair amount of sulphur, phosphorus, and organic matter, while others are deficient in these respects. The Chicago soils have a fairly good content of phosphorus, and a rather high content of sulphur and organic matter. Although the sulphate sulphur content of the Chicago soils is high, this accounts for little of the total sulphur, most of it being due to the large amount of organic matter present.

2. Most of the sulphur of soils is in organic form. There is a general correlation between the sulphur and organic matter content, soils of a high organic matter content having in general a high sulphur content. The surface soils are in general higher in sulphur than the subsoils.

3. Judging from the results obtained and the work of other investigators, sulphur fertilization should prove quite generally beneficial on the Atlantic coast and the Gulf coast. The same thing may be true of the Pacific coast. Sulphur fertilizers are probably not as generally needed in the central states, many soils no doubt needing them, and many others not. Soil of a high organic matter content, such as the Chicago soils, may not need sulphur fertilizers except for high sulphur-using crops. In case the sulphate sulphur is as great in amount as it is in the Chicago soils, sulphur fertilizers might not be needed, even if the organic matter content is low. Attempts are made, in the case of several soils, to correlate the sulphur, phosphorus, and organic matter content with the production of the soils, previous treatment, or other factors.

4. No definite conclusions can be drawn from the data as to the relation of sulphur to chlorophyll development in plants. This may come about through the effect of the sulphur in increasing the nitrogen content of the plants.

5. Flowers of sulphur and sodium sulphate, containing the same amount of sulphur as 100 pounds of gypsum per acre, and gypsum at rate of 500 pounds per acre, caused increased dry weights of sweet corn of 35–66 per cent. Larger amounts of flowers of sulphur and sodium sulphate gave no increases. The corn fertilized with sulphur had a higher moisture content than the controls. In the case of the gypsum series this amounted to 5 per cent.

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